BART SEISMIC UPGRADE – HOW MUCH?

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SUMMARY

This paper summarizes a seismic risk analysis of the Bay Area Rapid Transit (BART) system (Figure 1). The analysis shows that a $1.3 Billion seismic mitigation program is warranted. The paper describes how the money was raised.

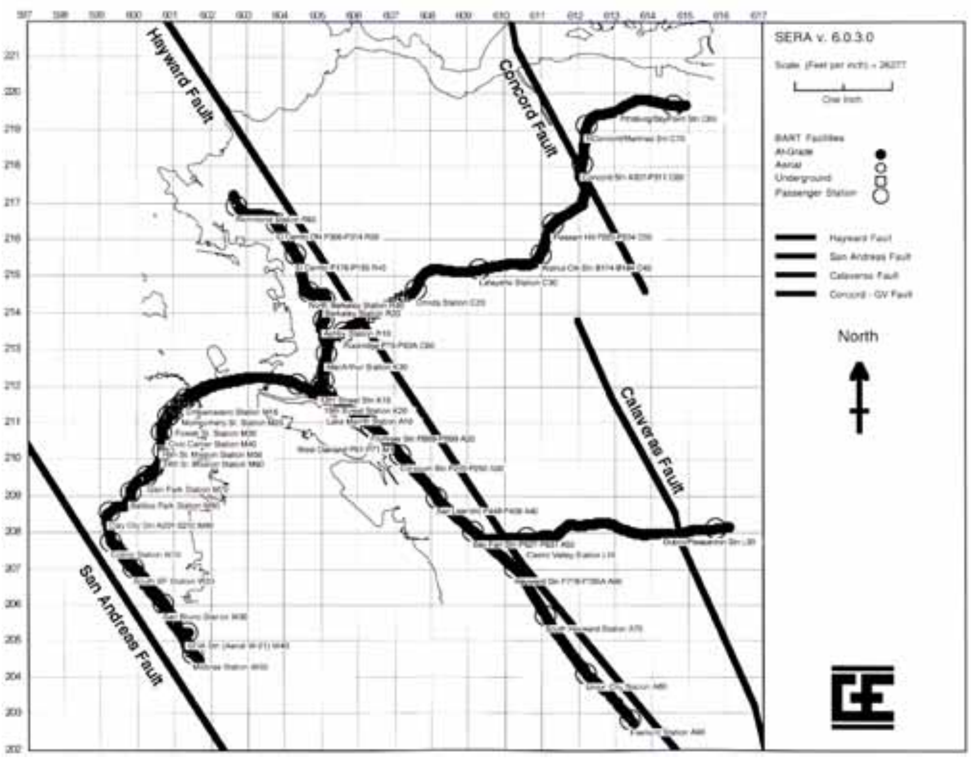

Figure 1. BART System, Showing Location of Nearby Faults

INTRODUCTION

The Seismic Risk Analysis includes assessments of:

1. How the existing BART system might perform after large earthquakes on the San Andreas, Hayward, Calaveras and Concord faults.

2. How a seismically-upgraded BART system might perform after these same earthquakes, assuming implementation of any of five different retrofit alternatives (called Packages 1, 2, 3, 4, 5).
3. The benefits and costs of the six alternatives: do nothing, or implement any of the five retrofit packages. This assessment is done using benefit-cost analyses.

INVENTORY

The Seismic Risk Analysis was performed for essentially every structure and piece of equipment in the BART system, including 10,106 track, embankment, aerial girders components; 1,983 aerial columns; 27 bored tunnels; 28 cut-and-cover tunnels; 57 Transbay tube segments; 43 passenger stations; 90 ventilation facilities; 68 electric substations; 40 circuit breaker stations; 21 maintenance yard buildings; 7 multi-story parking lots; 17 non-occupied equipment buildings; and most administrative and operations buildings. The analyses were performed using the System Earthquake Risk Assessment (SERA) program. The SERA program is a specialized geographical information system for planning- and real time seismic evaluation of complex and geographically distributed lifeline systems (G&E, 2004). The analysis includes a total of 15,078 individual structures and pieces of equipment located at 3,089 sites within the BART system. The year 2002 replacement value for these components is $10.85 Billion, excluding the value of land.

SCENARIO EARTHQUAKES

The BART system was analyzed for four scenario earthquakes (Table 1). The scenario earthquakes represent the most likely earthquakes in the Bay Area that would cause considerable damage to the BART system.

Earthquake Source Fault	Magnitude M_w	Where (Approximately)
Hayward	7.0	From Richmond to Fremont
San Andreas	8.0	From North of Fort Bragg to south of Palo Alto
Calaveras	6.8	From Danville to south of Pleasanton
Concord	6.8	From Concord to north of Fairfield

Table 1. Scenario Earthquakes for Evaluation of BART System

Ground motions were calculated at each of the 3,089 locations of BART structures and equipment. The effects of ground shaking, liquefaction, landslide and surface fault offset were included. The project reports (G&E 2002) and Litehiser et al (2003) provide comprehensive descriptions. The BART system was evaluated in its Status Quo condition, and for five possible retrofit alternatives, Table 2.

Retrofit Alternative	Description	Total Cost ($1,000,000)
Package 1.	Upgrade aerial structures, passenger stations, occupied buildings, the Transbay Tube and equipment to provide a "life safety" level of upgrade	$729
Package 2.	All Package 1 retrofits, plus Operability Improvements from Rockridge Station to Daly City Yard, additional upgrade to the Lake Merritt Administration building, plus additional upgrades to equipment	$828
Package 3.	All Package 2 retrofits, plus Operability Improvements from MacArthur Station to North Berkeley Station and from the Oakland Wye to Coliseum Station	$882
Package 4.	All Package 3 retrofits, plus Operability Improvements from Coliseum Station to South Hayward Station	$972
Package 5.	All Package 4 retrofits, plus Operability Improvements from South Hayward Station to Fremont Station, North Berkeley Station to Richmond Station, Orinda Station to Pittsburg / Bay Pointe Station	$1,118

Table 2. Retrofit Cost Summary ($2002)

RESULTS OF SCENARIO ANALYSES

Each of the 15,078 structures and pieces of equipment were evaluated for 100 simulations for each of the four scenario earthquakes. The impacts for each scenario earthquake are presented in several ways:

- The cost to repair damage to BART structures and equipment. This is calculated using fragility curves. Each set of fragility curves for each component includes a series of damage states for inertial (or where applicable) permanent ground deformation movements; cost and time needed to make emergency repairs (like temporary bracing); cost and time needed to make permanent repairs; life-safety potential. Fault trees are used to consider the overall impact of a facility should a series of individual damage states occur.
- The number of riders that will leave the BART system while the damage is being repaired. This includes a BART-system wide model showing the number of riders making a trip from station A to B under normal (non-earthquake) conditions. After the earthquake, some of these station pairs will remain out of service until sufficient repairs are made to all significant damage between the stations. The model allocates crews to repair components between the highest ridership stations, thereby tracking the restoration of ridership for each day after the earthquake until the entire system is functional.
- The number of sites in the BART system that sustain enough damage to cause a potential serious chance of fatality or injury to BART riders or BART employees.

- All results are tracked in terms of the range of outcomes for 100 simulations for each scenario earthquake. For example, it might take 894 days (average) to fully restore service after a Hayward M 7 earthquake; or 746 days (16th percentile) or 1,041 days (84th percentile).

Table 3 summarizes these impacts for one scenario earthquake for the BART system in its Status Quo (as-is) condition, or in each alternative retrofit condition.

BART System Condition	Direct Damage ($ Millions)	Lost Ridership (Millions of Trips)	Sites with Significant Life Safety Potential
Status Quo	$1,097	82.4	286
Package 1	341	41.2	5
Package 2	310	21.2	5
Package 3	295	20.1	5
Package 4	269	18.5	5
Package 5	198	17.0	4

Table 3. Summary Impacts – Hayward M 7 Scenario Earthquake

Ridership losses are calculated using a BART system model. A few of the key issues: there are normally (as of mid-2002) about 250,000 average daily riders (average over 7 days – ridership on weekdays is higher); in the "status quo" condition, the undamaged part of BART can carry about 70,000 rides per day within a couple of days; then increasing to 125,000 rides per day upon completion of repair to aerial structures; then increasing to 240,000 rides per day once the Transbay Tube is put back in service; and finally increasing to 250,000 rides per day once the Berkeley Hills Tunnel is returned to normal service in about 2.3 years.

Figure 2 shows pie charts with the cumulative impacts caused by damage to the BART system for each of the four scenario earthquakes. Each pie chart is divided into six parts. The meaning of the pie charts is as follows:

- Repair costs. These are the out-of-pocket costs to BART to make the repairs following the earthquake.
- Fare box revenue losses. This is the lost revenue to BART from the impact of loss of ridership due to damage to the system.
- Bus bridge cost. This is the cost to BART to operate bus bridges following the earthquake.
- Economic impact to BART riders. This is the cost to BART riders who take alternate transportation to reach their destinations, given that BART service is not available due to earthquake-caused damage to the BART system.
- Economic impact to Bay Area commuters. This is the cost to Bay Area commuters who are impacted by the increased congestion caused by the BART riders who take alternate transportation to reach their destination.

- Monetized casualty loss. This is the economic value of injuries and fatalities caused by earthquake-caused damage to the BART system.
- Number directly below each pie chart: the total scenario loss (year 2002 dollars). This is the sum of all the "wedges" of each pie chart. For example, the total scenario loss for the Hayward M 7.0 earthquake for BART in its Status Quo condition is $4,841,000,000.
- The order of the legend corresponds to a clockwise depiction of each "wedge" in the pie chart, beginning with the 12 o'clock position.

For example, Figure 2 shows that the expected economic impacts to the Bay Area are $4.841 Billion (year 2002 dollars) should a Hayward Magnitude 7 earthquake occur before BART implements any seismic retrofit program. About one quarter of the losses are "out of pocket" costs to BART (the sum of the cost to make repairs, lost fare box revenue and the cost to operate bus bridges while repairs are made). The remainder of the losses accrue to BART riders and Bay Area commuters, mostly due to the disruption of commute patterns, and some due to the potential for casualties. Assuming that BART implements retrofit Package 2, then the scenario losses are reduced from the Status Quo case by an average of 80%.

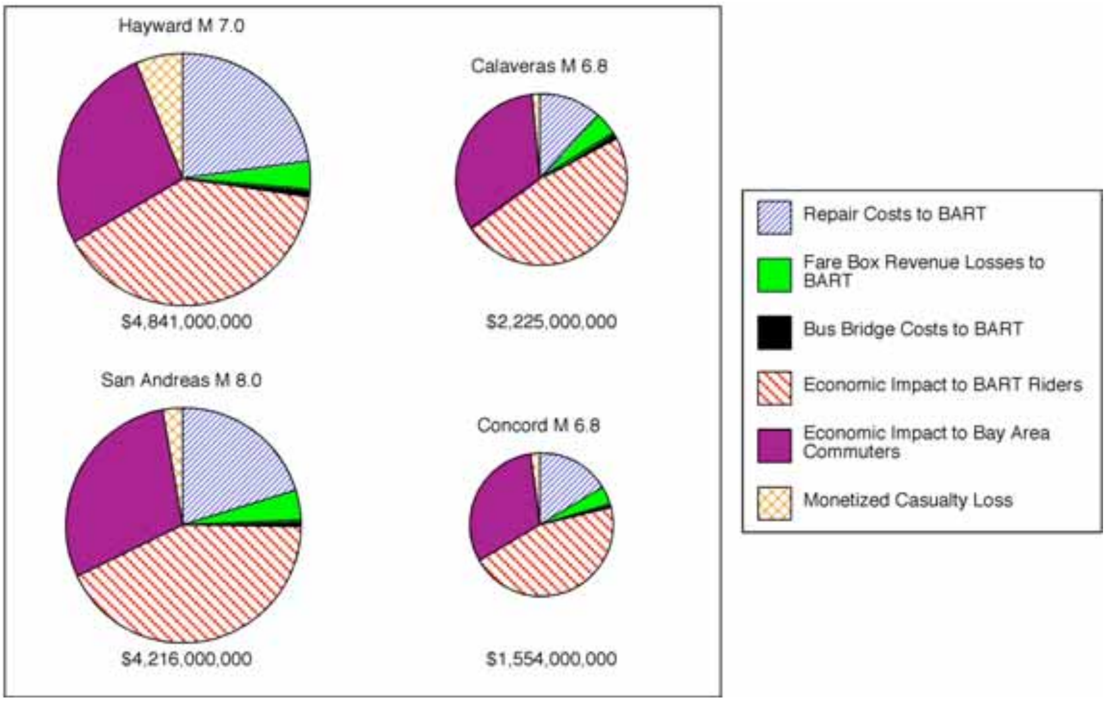

Figure 2. Total Impact of Scenario Earthquakes – BART System in its Status Quo Condition

BENEFITS AND COSTS OF SEISMIC UPGRADE

A Benefit Cost Analysis was performed to establish the relative cost effectiveness of each of the six retrofit alternatives. A Benefit Cost Ratio (BCR) of 1 or higher shows that the cost for the retrofits is less than the net present value of the benefits (benefits =

reduction in future losses) from earthquakes, in consideration of the time value of money, the probabilities of different sized earthquakes, and their impacts. The four faults listed in Table 2 plus various magnitude earthquakes on additional faults were considered for purpose of benefit cost analysis. The three main impacts (direct damage, loss of ridership, life safety) were monetized for purposes of the Benefit Cost Analysis. The BCR values are based on the incremental benefit of each more expensive retrofit alternative. Table 4 summarizes the findings.

BART Condition	Incremental Costs ($millions)	Incremental Benefits ($millions)	Benefit-Cost Ratio
Status Quo	n/a	n/a	n/a
Package 1	$729	$2,394	3.28
Package 2	$98	$225	2.29
Package 3	$55	$23	0.42
Package 4	$90	$38	0.42
Package 5	$146	$67	0.46

Table 4. Costs and Benefits of Each Retrofit Alternative ($2002)

Based on these findings, seismic retrofit of the BART system is economically sound, for either retrofit alternatives Package 1 or 2. Seismic retrofit Packages 3, 4 and 5, do not appear to be justifiable on an economic basis.

Besides the benefit-cost ratios given above, many other quantifiable and less tangible factors need and have been considered in recommending a retrofit package. One factor was the consequences of using deterministic acceptance criteria (like stresses, strains, allowable demand to capacity ratios, etc.), and allowing more damage and longer restoration/repair time in selected segments of the system versus incremental cost. Another factor was the level of uncertainty associated with specific fragility relationships, and associated risk due to the uncertainty. Broader economic impacts to the Bay Area from the extended loss of a vital, established, public transportation system, which might include loss of business, lowered real estate values, reduced consumer spending, etc., were not directly included in the benefit cost analysis. Since the "Package 5" option returns more of this vital transportation system to operation sooner, these broader impacts would be reduced, compared to the "Package 2" option. Although Caltrans and many cities are conducting retrofit programs of their own, the possibility of road closures and disruptions to other forms of transportation after a large earthquake remains. Experience following the Loma Prieta earthquake showed that BART system ridership could increase as a result. In addition, the impact of post-earthquake repairs on local communities near the BART alignment will be less if the "Package 5" option is implemented, since there will be fewer repairs required.

IMPLEMENTATION

The vulnerability study uncovered unanticipated safety risks that led to the decision to place a Bond Measure on the November 2002 ballot. Although the BART Board was concerned about the short time available for campaigning, experts on both the Bechtel Design Review Panel and the Independent Peer Review Panel recommended that the vulnerabilities be addressed and mitigated as soon as practical.

Based on the findings of the seismic risk analysis, it was apparent that seismic retrofits included with Package 1 or 2 were the most cost effective. Additional retrofits beyond the package 2 level appear to provide decreasing benefits. The Retrofit Measure (bonds that would be repaid via property tax assessments) was put on the ballot in three counties: San Francisco, Alameda and Contra Costa. This bond measure would have provided funds to implement package 2 (with allowance for inflation). Despite a short campaign with very little publicity, the Bond almost passed. In San Francisco, Alameda and Contra Costa Counties, the bond measure had a 73.4%, 66.6% and 54.4% "yes" vote respectively. To pass the bond, the required cumulative "yes" vote was two-thirds majority, while the actual cumulative "yes" vote was 64.2%. Thus, the measure failed.

Following the defeat of the Bond Measure, BART continued its seismic retrofit program, but at a significantly reduced scope due to lack of funding. The focus was on the Transbay Tube, which is the component that would have the most significant impact on safety and the operability of the system. Steps were also taken to improve post-earthquake assessment of the system and emergency response. BART worked with the USGS to install 10 strong motion instruments at its passenger stations, and upgraded its SERA simulation software to allow near-real-time processing of ShakeMap data. The revised software will allow BART to see the likely damage and operational status of all its facilities in near-real-time, which will allow BART to make informed and timely post-earthquake decisions as to whether specific facilities/segments are safe enough to move trains, and whether and where engineers should be sent out to inspect for damage. Displacement sensors are also being placed at critical underwater joints in the Transbay Tube.

Due to the concern about the impact on safety and the Bay Area economy without a retrofitted BART system, a new funding request was placed on the 2004 ballot. To better define and quantify the impact on traffic without BART, a traffic study by U.C. Berkeley (Cassidy, 2004) was commissioned. amongst other impacts, this traffic study showed that without the BART Transbay Tube, congestion from the Bay Bridge westbound in the morning would create backups stretching 26 miles with vehicles traveling as slow as 9 miles per hour. In the afternoon, heading east, the Bay bridge backup would stretch 31 miles with an average travel speed of 11 miles per hour. Rush "hour" would increase from the current two hours to nearly seven hours. Funding to publicize the BART Bond Measure was very limited, yet it was recognized that the prudence of retrofitting the system needed to be communicated better to the voters. Polls indicated that the best persons to communicate the message to the voters were technical experts. Potential voters indicated that technical experts were much more trusted and had much better credibility than BART personnel, politicians, or any other group. Due to the process used to determine the need, benefit and scope of the retrofit program, BART was able to get the active support from many technical experts and organizations. The Vulnerability Analysis, Risk Analysis and use of expert review panels were essential to demonstrate that BART’s program was necessary and cost/effective, and to gain the support from the technical community. The Northern California Branch of EERI provided written endorsement for the Bond Measure, sponsored or co-sponsored several press events that provided public exposure for the BART retrofit program, and provided technical experts to speak at conferences, newspaper editorial broads, etc. Help from the technical community was essential to gain needed support, especially since no television and very limited radio advertisement was done because of the lack of campaign funds (BART could not contribute by law). It is likely that the Bond Measure would not have passed without the enthusiastic support of the technical community.

In November 2004, the voters approved a $980 million bond to fund this seismic retrofit program, by a 67.9% to 32.1% margin. Property owners will pay for this bond via a tax assessment with an estimated average $7.04 per $100,000 of assessed value.

As of late 2004, the inflation-adjusted program is estimated to cost $1.307 billion. The sources of funds are as follows: $143 million (bridge toll increase); $134 million (Caltrans, to upgrade bridges over Caltrans' highways); $50 million (BART operations); $980 million (November 2004 Bond Measure). The current budget for design and construction is: $699 million (aerial trackway structures); $355 million (underground trackway structures, including the Transbay Tube); $25 million (at-grade trackway structures); $157 million (passenger stations); $50 million (administrative, maintenance and operations facilities); $21 million (bond issuance and election costs).

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